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Metals and ionizing photons from dwarf galaxies

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ABSTRACT

We estimate the potential contribution of $M < 10^9\,\mathrm{M}_\odot$ dwarf galaxies to the reionization and early metal enrichment of the Milky Way environment, or circum-Galactic medium. Our approach is to use the observed properties of ancient stars ($\gtrsim$12 Gyr old) measured in nearby dwarf galaxies to characterize the star formation at high z. We use a merger-tree model for the build-up of the Milky Way, which self-consistently accounts for feedback processes, and which is calibrated to match the present-day properties of the Galaxy and its dwarf satellites. We show that the high-z analogues of nearby dwarf galaxies can produce the bulk of ionizing radiation (>80 per cent) required to reionize the Milky Way environment. Our fiducial model shows that the gaseous environment can be 50 per cent reionized at $z \approx 8$ by galaxies with $10^7\,\mathrm{M}_\odot \le M < 10^8\,\mathrm{M}_\odot$. At later times, radiative feedback stops the star formation in these small systems, and reionization is completed by more massive dwarf galaxies by $z_{\rm rei} = 6.4 \pm 0.5$. The metals ejected by supernova-driven outflows from $M < 10^9\,\mathrm{M}_\odot$ dwarf galaxies almost uniformly fill the Milky Way environment by $z \approx 5$, enriching it to $Z \approx 2 \times 10^{-2}\,\mathrm{Z}_\odot$. At $z \approx 2$, these early metals are still found to represent the ≈50 per cent of the total mass of heavy elements in the circum-Galactic medium.

Key words: galaxies: dwarf – galaxies: high-redshift – Local Group – cosmology: theory.

1 INTRODUCTION

The nature of the first astrophysical sources that reionized the intergalactic medium (IGM) by $z \le 6$ (Fan et al. 2006), and possibly controlled its metal enrichment up to $Z \ge 10^{-4}\,\mathrm{Z}_\odot$ (Songaila 2001; Ryan-Weber et al. 2009) is still a matter of debate. Recent models and observations of cosmic reionization require an increasing UV emissivity towards high redshifts, and suggest that undetected faint galaxies, $M_{\rm UV} > -18$, must have significantly contributed to reionization (e.g. Bolton & Haehnelt 2007; Salvaterra, Ferrara & Dayal 2011; Alvarez, Finlator & Trenti 2012; Bouwens et al. 2012; Finkelstein et al. 2012; Kuhlen & Faucher-Giguère 2012; Mitra, Ferrara & Choudhury 2013). Supernova-driven outflows from dwarf galaxies are likely to be one of the most efficient mechanisms to transport metals into the IGM (e.g. Mac Low & Ferrara 1999; Madau, Ferrara & Rees 2001; Scannapieco, Ferrara & Madau 2002), making these systems the obvious candidates for polluting it. However, the physical properties of high-z dwarfs are very uncertain, and their formation is predicted to be progressively suppressed during reionization by the increased UV radiation field intensity (e.g. Ciardi & Ferrara 2005).

Ancient ($\gtrsim$12 Gyr) metal-poor stars observed in nearby dwarf spheroidal galaxies (dSphs) offer the unique opportunity to look back at the star formation (SF) properties of these small systems during the epoch of reionization (Salvadori & Ferrara 2009, hereafter SF09). These ancient stars were formed before the gravitational interaction with the Galaxy could have substantially altered the evolution of dSphs (e.g. Ibata et al. 2001; Peñarrubia, Navarro & McConnachie 2008). Thus, their observed features, reflect the intrinsic evolution of high-z dwarfs, along with the (possible) influence of dissociating/ionizing radiation. Nearby dSphs have been studied in great detail, and an ancient stellar population has been observed in all of them (e.g. Tolstoy, Hill & Tosi 2009). The Sculptor dSph is a typical example of 'classical' dSphs, which have total luminosity $L \approx (10^5\text{–}10^{7.5})\,\mathrm{L}_\odot$ and total mass $M \approx (10^8\text{–}10^9)\,\mathrm{M}_\odot$, and stars older than 12 Gyr represent $\gtrsim$55 per cent of its total stellar mass (de Boer et al. 2012a). Ultra-faint dwarf galaxies, $L < 10^5\,\mathrm{L}_\odot$ and $M < 10^8\,\mathrm{M}_\odot$, seem to show no evidence for stars younger than 12.5 Gyr (Brown et al. 2012; Dall'Ora et al. 2012; Okamoto et al. 2012), suggesting that the SF activity might have been suppressed by a global event, such as reionization.

In this *Letter*, we focus on the high-redshift ($z > 5$) analogues of Milky Way (MW) dwarf galaxies to investigate the impact of these systems on the reionization *and* metal enrichment of the MW environment, the formation medium of the Galaxy and its dwarf satellites. We use the data-calibrated cosmological code GAlaxy MErger Tree and Evolution [GAMETE; SF09, Salvadori, Schneider & Ferrara (2007) and Salvadori & Ferrara (2012), hereafter SSF07 and SF12], which has been developed to investigate the properties

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of present-day ancient metal-poor stars, and which successfully reproduces the metallicity–luminosity relation of MW dwarf galaxies (SF09), the stellar Metallicity Distribution Function (MDF) observed in the Galactic halo (SSF07), in classical, and in ultra-faint dwarf galaxies (SF09).

2 DATA-CALIBRATED MODEL

GAMETE reconstructs possible merger histories of an MW-sized dark matter halo, $M_{\rm mw} = 10^{12}\,{\rm M}_{\odot}$, by using a Monte Carlo algorithm based on the Extended Press-Schechter theory (SSF07). The SF is traced along the merger trees by adopting physically motivated hypotheses: (a) there exists a minimum halo mass to form stars, $M_{\rm sf}(z)$, whose evolution accounts for the suppression of SF in progressively *more massive* objects due to the increasing photodissociating/ionizing radiation (fig. 1 of SF09), (b) the SF rate is proportional to the mass of cold gas in each galaxy, and it is regulated via the SF efficiency, ϵ_*, (c) in *minihaloes* with virial temperatures $T_{\rm vir} \lesssim 10^4$ K, the SF efficiency is reduced as $\epsilon_{\rm H_2} = 2\epsilon_*[1 + (T_{\rm vir}/2 \times 10^4 K)^{-3}]^{-1}$ to account for the ineffective cooling by molecular hydrogen, H_2 (SF09), (d) Population II (Pop II) stars form according to a Larson initial mass function (IMF; SSF07) if the metallicity of the gas exceeds the critical value, $Z_{\rm cr} \approx 10^{-5\pm1}\,{\rm Z}_{\odot}$, which sets the minimal conditions to trigger the formation of low-mass stars (Schneider et al. 2002); if $Z < Z_{\rm cr}$ then Population III (Pop III) stars form, with the IMF discussed in Section 3.

The chemical evolution of the gas is simultaneously traced in the haloes and in the surrounding MW environment by including the effect of SN-driven outflows, which are controlled by the SN-wind efficiency, ϵ_w (SF12). The total volume filled by metals, $V_{\rm tot}(z)$, is computed at each z as the sum of the volume of individual metal bubbles around star-forming haloes, $V^i_{\rm s}(z)$. The time evolution of each bubble is obtained by solving the canonical momentum and energy conservation equations derived adopting the thin-shell approximation (Madau et al. 2001, equations 24 and 25). This can be translated into a volume filling factor, Q_Z, given by

$$Q_Z = \frac{V_{\rm tot}(z)}{V_{\rm mw}(z)} = \frac{4\pi}{3V_{\rm mw}(z)}\Sigma_i[R^i_{\rm s}(z)]^3, \tag{1}$$

where $R^i_{\rm s}(z)$ is the shell radius, whose expansion is driven by the energy input of the ensemble of SNe exploding in each star-forming halo. The proper MW volume, $V_{\rm mw}(z)$, is estimated at the turn-around radius, $V_{\rm mw}(z) \approx M_{\rm mw}/[5.55\Omega_{\rm m}\rho_{\rm cr}(z)] \approx 5\,{\rm Mpc}^3\,(1+z)^{-3}$.

The SF and SN wind efficiencies are fixed to reproduce the global properties of the MW (SSF07). The low-Z tail of the Galactic halo MDF allows us to constrain $Z_{\rm cr} \le 10^{-4}\,{\rm Z}_{\odot}$, here fixed to the best-fitting value, $10^{-4}\,{\rm Z}_{\odot}$ (SSF07). The reconstructed evolution of $M_{\rm sf}(z)$, correctly matches the observed metallicity–luminosity relation of MW dwarf galaxies (SF09), and it implies a reionization history that is consistent with the early/late reionization models of Gallerani, Choudhury & Ferrara (2006) (see fig. 1 of SF12).

2.1 Ionizing photon production

The cumulative rate of ionizing photons produced by stellar populations with different ages and metallicities is computed along the merger trees by including the results of population synthesis models in GAMETE. We use STARBURST99[1] (Leitherer et al. 1999) to obtain the evolution of the ionizing photon production rate per stellar mass formed, $q(t, Z)$, during each burst of SF with $Z = [0.02–1]\,{\rm Z}_{\odot}$. Because of the limited metallicity range we use $q(t, Z_{\rm min})$ for bursts of Pop II stars for $Z \le 0.02\,{\rm Z}_{\odot}$, and we follow the results of Schaerer (2003) to compute $q(t, 0)$ for Pop III stars. At each z, the rate of ionizing photons per unit volume injected into the MW environment, $\dot{n}_\gamma$, is then computed as

$$\dot{n}_\gamma(z) = V^{-1}_{\rm mw}\Sigma_i\,[f_{\rm esc}\,q(t_z - t_{z_i}, Z)\,M_*(z_i, Z)]\;, \tag{2}$$

where $M_*(z_i, Z)$ is the mass of stars with metallicity Z formed at z_i, and $f_{\rm esc}$ is the escape fraction of ionizing photons, which may depend on the nature of the stellar sources and z. The evolution of the filling factor of ionized regions, $Q_{\rm H\,II}$, is obtained by integrating:

$$\frac{{\rm d}Q_{\rm H\,II}}{{\rm d}t} = \frac{\dot{n}_\gamma}{n^{\rm mw}_{\rm H}} - \frac{Q_{\rm H\,II}}{t_{\rm rec}}, \tag{3}$$

where $n^{\rm mw}_{\rm H}$ is the comoving hydrogen number density of the MW environment, and $t_{\rm rec} = [C\alpha_B\,n^{\rm mw}_{\rm H}\,(1+z)^3]^{-1}$ is the hydrogen recombination time, with C clumping factor and $\alpha_B = 2.6 \times 10^{-13}\,{\rm cm}^3\,{\rm s}^{-1}$ recombination rate. We estimate $n^{\rm mw}_{\rm H} = M_{\rm gm}(z)/(\mu m_p V_{\rm mw})$, as the ratio between mass of gas in the MW environment, $M_{\rm gm}(z) \approx (\Omega_{\rm b}/\Omega_{\rm m})[M_{\rm mw} - M_{\rm coll}(z)]$, and the comoving MW volume, where $M_{\rm coll}(z)$ is the total mass in collapsed haloes. We find $n^{\rm mw}_{\rm H} \approx (5.4 - 4.2)\,n^0_{\rm H}$ for $z = (20 - 5)$, where $n^0_{\rm H}$ is the hydrogen number density in the IGM.

3 RESULTS

The contribution to the total stellar mass, $M_*(>z)$, of haloes within different mass ranges is shown in Fig. 1(a) as a function of redshift. We can see that the evolution of $M_*(>z)$ is dominated by haloes with increasing M for decreasing z, which is a consequence of hierarchical galaxy formation. Those haloes with $M < 10^9\,{\rm M}_{\odot}$, represent the dominant contributors until $z \approx 6$, when $M_*(>z) \approx 2 \times 10^9\,{\rm M}_{\odot}$. Pop III stars form in $M < 10^8\,{\rm M}_{\odot}$ objects, and already at $z < 15$ they are sub-dominant with respect to Pop II stars. However, to avoid overestimating the photons/metals that can be contributed by low-mass dwarf galaxies, we adopt a conservative hypothesis and assume Pop III stars to have standard IMF and $m_{\rm PopIII} = (1100)\,{\rm M}_{\odot}$ (see SSF07).

The stellar mass required to reionize the MW environment, $M_* \ge M_{\rm gm}(1 + N_{\rm rec})/(f_{\rm esc}N_\gamma)$, can be estimated by recalling that $N_\gamma \approx 4000$ ionizing photons are produced per baryon in stars with metallicity $Z \ge 1/20\,{\rm Z}_{\odot}$ and distributed with a Salpeter IMF. Assuming that only 10 per cent of these photons escape galaxies, taking $M_{\rm gm} \approx \Omega_{\rm b}/\Omega_{\rm m}M_{\rm mw}$, and ignoring recombinations, $N_{\rm rec} = 0$, we get $M_* \ge 4.25 \times 10^8\,{\rm M}_{\odot}$. This implies (Fig. 1a) that $M < 10^9\,{\rm M}_{\odot}$ haloes can be responsible for the reionization of the MW environment, which is expected to occur at $z_{\rm rei} \lesssim 9$. So, what are the present-day analogues of these high-z objects?

Galaxies with total masses $10^7\,{\rm M}_{\odot} \le M < 10^8\,{\rm M}_{\odot}$ formed at $z \le 10$ are mostly minihaloes, $T_{\rm vir} \propto M^{2/3}(1+z) < 10^4$ K. The ones that are not incorporated into larger galaxies are expected to be observed today as ultra-faint dwarf galaxies (SF09). Their tiny stellar masses ($10^3\,{\rm M}_{\odot} \lesssim M_* < 10^5\,{\rm M}_{\odot}$) reflect both their low *mean SF rate*, $\langle\Psi\rangle$, and their short SF activity (Fig. 1b). The low $\langle\Psi\rangle$ is due to the ineffective cooling by H_2 molecules and gas-loss, driven by SNe. The limited duration is a consequence of reionization, as

[1] http://www.stsci.edu/science/starburst99

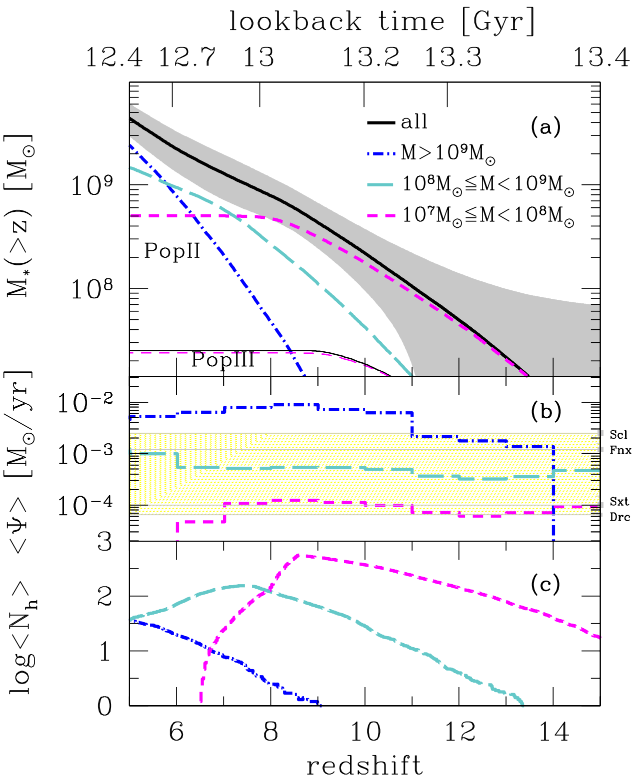

Figure 1. (a) The cumulative stellar mass, $M_*(>z)$, (solid line), (b) the mean SF rate, $\langle\Psi\rangle$, and (c) the mean number of star-forming haloes, $\langle N_h\rangle$, as a function of z. The lines show the contribution to these physical quantities by haloes within different mass ranges given in (a). The results are averaged over 50 MW merger histories, and the $\pm1\sigma$ dispersion is indicated by the shaded area in (a). The Pop II/Pop III contribution to $M_*(>z)$ is shown in (a). The shaded area in (b) shows the range of $\langle\Psi\rangle$ measured in MW classical dSphs, the horizontal lines are measurements for: Sculptor (de Boer et al. 2012a), Fornax (de Boer et al. 2012b), Sextans (Lee et al. 2009), Draco (Aparicio, Carrera & Martínez-Delgado 2001).

shown in Fig. 1(c) that displays the *average number of star-forming haloes*, $\langle N_h\rangle$, for different mass ranges. Haloes with $M < 10^8\,\mathrm{M}_\odot$ are ≈10 times more abundant than more massive objects at $z > 9$, but their $\langle N_h\rangle$ rapidly declines for $z < 8.5$ due to the increased Lyman–Werner (LW) background that photodissociates H_2 in minihaloes, turning them into sterile systems (SF12). Following reionization, gas accretion stops for $T_{\rm vir} < 2\times10^4$ K objects, quenching the SF in the lowest mass galaxies. These findings are in agreement with the *Hubble Space Telescopes* results for ultra-faint dwarfs SF histories (Brown et al. 2012).

Galaxies with $10^8\,\mathrm{M}_\odot \le M < 10^9\,\mathrm{M}_\odot$, mainly form at $z < 11$ by the merging of less massive progenitors. They are expected to be the high-z analogues of classical dSphs (SF09). These galaxies are not affected by LW background, and continue forming stars after the end of reionization ($z < 6$, Fig. 1b) although they slowly decrease in number (Fig. 1c) as they merge into more massive systems. At $z > 5$, the predicted $\langle\Psi\rangle$ for these galaxies is consistent with the mean value measured for the oldest stellar population (>12.5 Gyr) of the classical MW dSphs, as seen in Fig. 1(b).

Galaxies with $M > 10^9\,\mathrm{M}_\odot$ assembled at $z < 9$ by the merging of smaller galaxies (Fig. 1c). They are typically associated with the major components of the MW, which at $z \approx 6$ have masses $M \approx 10^{9.5}$–$10^{11}\,\mathrm{M}_\odot$ (Salvadori, Dayal & Ferrara 2010).

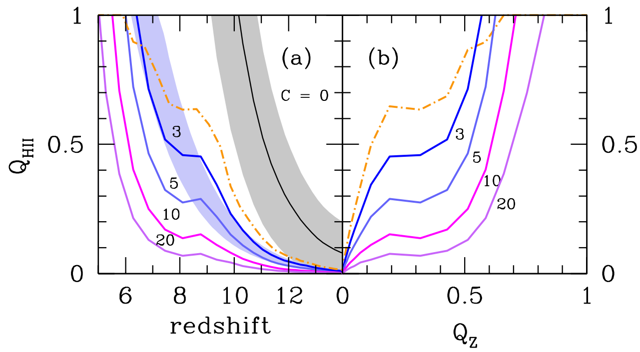

Figure 2. (a) The filling factor of ionized regions in the MW volume, $Q_{\rm H\,II}$, at different z. The *solid curves* show the results for $f_{\rm esc} = 0.1$ and for increasing clumping factors, C, (from top to bottom). The *dot–dashed curve* shows the $Q_{\rm H\,II}$ evolution obtained by assuming $C = 4$ and $f_{\rm esc}(z)$ (Mitra et al. 2013). All results are averaged over 50 MW merger histories. The *grey shaded area* shows the $\pm1\sigma$ dispersion for the case $C = 0$. The *blue shaded* area delimits the early/late reionization histories by Gallerani et al. (2006). (b) The volume filling factors of metals, Q_Z, versus ionized regions, $Q_{\rm H\,II}$, for different C-$f_{\rm esc}$ combinations.

Now we can use our model to quantify the impact of the $z > 5$ analogues of present-day dwarf galaxies, i.e. $M < 10^9\,\mathrm{M}_\odot$ haloes, on the evolution of the MW environment.

3.1 Reionization sources

The evolution of the volume filling factor of ionized regions, $Q_{\rm H\,II}$, is shown in Fig. 2(a) for different values of the clumping factor C, and $f_{\rm esc} = 0.1$. The growth of $Q_{\rm H\,II}$ is regulated by the balance between the rates of ionization, $\dot N_\gamma$, and recombination, $\dot N_{\rm rec} = n_{\rm H}^{\rm mw}\, V_{\rm mw}\, t_{\rm rec}^{-1} = \alpha_B\, C\, (n_{\rm H}^{\rm mw})^2 V_{\rm mw}(1+z)^3$. If recombinations are ignored, i.e. $C = 0$, then $Q_{\rm H\,II}$ increases steeply, and the MW gets reionized at $z_{\rm rei} \approx 10$ ($Q_{\rm H\,II} = 0.99$). Reionization is delayed if larger C values are assumed, although all models with $C > 0$ are consistent with $z_{\rm rei} \approx 6$ within 2σ errors. At $z \ge 10$, recombinations easily balance ionizations provided that C is large. Thus, the larger is C, the more gentle is the slope of the curve. At $z \approx 8.5$, the growth of $Q_{\rm H\,II}$ temporarily decreases because of both the disappearance of Pop III stars, producing more ionizing photons than Pop II (Schaerer 2003), and the quenching of SF in minihaloes. The rise of $Q_{\rm H\,II}$ at $z \approx 7.5$ is due to $10^8\,\mathrm{M}_\odot \le M < 10^9\,\mathrm{M}_\odot$ dwarf galaxies, which become the dominant stellar (photon) sources (Fig. 1a). When $\dot N_\gamma \gg \dot N_{\rm rec}$ ionizations completely overcome recombinations, and the slope of $Q_{\rm H\,II}$ becomes independent of C. The higher is C, the later this condition is satisfied, and thus the lower is $z_{\rm rei}$.

The reionization histories obtained by assuming $C = 3$–5 (Fig. 2a), provide a satisfactory match to the $Q_{\rm H\,II}$ evolution implied by our choice of $M_{\rm sf}(z)$ (blue shaded area). So these models are self-consistent. An equally good agreement is achieved by adopting an escape fraction that increases with redshift,[2] and $C = 4$. In this case, the MW environment is ≈65 per cent reionized at $z \approx 8$, when $M < 10^9\,\mathrm{M}_\odot$ dwarf galaxies dominate the SF (Fig. 1a). Thus, $f_{\rm esc} = 0.1$ yields the most conservative results for dwarf galaxies. Within this assumption, we can inspect Fig. 3 where we show, as a function of $z_{\rm rei}$, the contribution of galaxies with different masses to the time-integrated comoving photon density, n_γ. We see that

[2] Linearly interpolating among the values of Mitra et al. (2013): $f_{\rm esc} = 0.179$ at $z \ge 8$ and $f_{\rm esc} = 0.068$ at $z \le 6$.

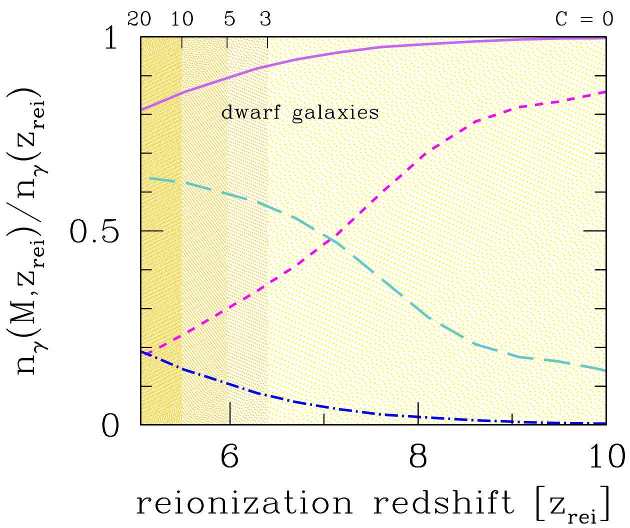

Figure 3. Time-integrated comoving photon density, n_γ, normalized to the total value at different reionization redshifts, z_{rei}. The mean contribution by haloes within different mass ranges is shown using the same lines as in Fig. 1(a). The solid curve shows the cumulative contribution by $M < 10^9\,M_\odot$ dwarfs. The shaded regions associate z_{rei} to the corresponding clumping factors, C.

$M < 10^9\,M_\odot$ dwarf galaxies are the *primary reionization sources* of the MW environment, providing >80 per cent of the ionizing photons independent of z_{rei}, and thus of C. Their contribution rises up to ≈93 per cent for our reference model ($C = 3$, $z_{rei} = 6.4 \pm 0.5$). At $z \geq 8$, the reionization process is driven by $M < 10^8\,M_\odot$ dwarf galaxies, which provide >70 per cent of n_γ. At $z \leq 8$, the photodissociating/ionizing radiation produced by the *same* dwarf galaxies quenches the SF in these systems, and the reionization is completed by $10^8\,M_\odot < M < 10^9\,M_\odot$ dwarf galaxies, which account for ≈55 per cent of the ionizing photon budget at $z_{rei} = 6.4$.

3.2 Metal polluters

The evolution of the metal filling factor, Q_Z, is shown in Fig. 4 along with the contribution of galaxies within different mass ranges.

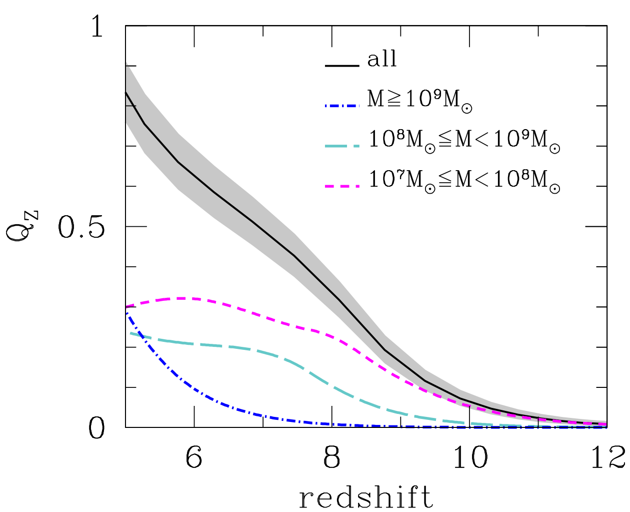

Figure 4. Evolution of the metal filling factor in the MW volume, Q_Z, averaged over 50 merger histories (solid line as in Fig. 1a). The contribution by galaxies with different masses is shown.

We find that metals fill ≈65 per cent of the MW volume by $z \approx 6$, and ≈100 per cent by $z \approx 4.5$, implying that the metal enrichment of the MW environment proceeds slower than reionization. In Fig. 2(b), the z-evolution of the two filling factors are plotted against each other, and we can see that $Q_Z < 1$ when $Q_{\rm H\,II} \approx 1$, independent of the assumed C value. In Fig. 2(b), we can also see the imprint of Pop III stars, which accelerate the early evolution of $Q_{\rm H\,II}$ but not Q_Z. This is because in our model Pop III stars are assumed to form with a standard IMF, and so they have harder spectra then Pop II but same SN explosion energy. Even with this conservative hypothesis, we find that at $z = 6$ *dwarf galaxies* can account for ≥90 per cent of the metal-enriched volume, and for ≥65 per cent at $z \approx 5$, when $Q_Z \approx 0.85$. At $z = 5$, we find that the gas in the MW environment is enriched up to an average metallicity $Z_{\rm gm} = M^Z_{\rm gm}/M_{\rm gm} \approx 2 \times 10^{-2}\,Z_\odot$ (see also fig. 4 of SSF07), and that >90 per cent of these metals have been ejected from $M < 10^9\,M_\odot$ dwarf galaxies. At lower z, radiative feedback processes (and merging) strongly reduce the SF in dwarf galaxies and thus their instantaneous metal-ejection rate. At $z \approx 2$ however, ≈50 per cent of $M^Z_{\rm gm}(z = 2)$ still originates from these high-z dwarfs, which therefore dominate the integrated contribution to the metal enrichment of the MW environment.

4 DISCUSSION

We used a data-calibrated cosmological model for the formation of the MW to show that the high-z counterparts of nearby dwarf galaxies could easily be the primary reionization sources and the early metal polluters of the MW environment. Our model predictions at $z > 5$ are consistent with the SF histories of MW dwarf galaxies: ultra-faint dwarfs stop forming stars before the end of reionization (Brown et al. 2012), which does not affect the evolution of the more massive classical dSphs (e.g. Monelli et al. 2010). The average SF rates predicted for $M < 10^9\,M_\odot$ dwarf galaxies are also within the observed range for the oldest stellar populations (see Fig. 1b), implying that their photon/metal contribution has not been overestimated.

Independent of z_{rei} (≥5), and thus of the parameters C and f_{esc}, we found that dwarf galaxies can produce >80 per cent of the ionizing photons required to fully ionize the MW environment, $n^{\rm mw}_{\rm H} \approx 4.5 n^0_{\rm H}$, in agreement with recent models and observations for cosmic reionization. As Choudhury, Ferrara & Gallerani (2008), we predict that reionization is initially driven by $M < 10^8\,M_\odot$ haloes, the progenitors of ultra-faint dwarf galaxies and the most common objects at $z > 8.5$. It is then completed by more massive dwarf galaxies, which are not affected by the radiative feedback processes that halt the SF in the smallest systems. The same $M < 10^9\,M_\odot$ dwarf galaxies that reionize the MW environment can also drive its early metal enrichment via SN-driven outflows (see also Madau et al. 2001). The metals ejected by dwarf galaxies can provide >90 per cent of the total mass of heavy elements in the MW environment at $z \approx 5$, when $Q_Z \approx 0.85$, and ≈50 per cent at $z \approx 2$. This implies that the high-z analogues of *present-day* dwarf galaxies could have dominated the metal enrichment of the gaseous environments surrounding galaxies for ≈10 Gyr, thus suggesting possible links between the chemical abundances observed in their ancient stellar populations and in the gas measured in distant QSO absorption lines.

For reasonable values of $C \leq 5$ (Pawlik, Schaye & van Scherpenzeel 2009), the reionization histories we found are compatible with our assumed evolution of the minimum mass for SF, $M_{sf}(z)$, which is determined by radiative feedback. Our fiducial model

($C = 3, f_{\rm esc} = 0.1$), which predicts $Q_{\rm H\,II} = 0.5$ at $z = 8 \pm 1$ and $Q_{\rm H\,II} = 0.99$ at $z_{\rm rei} = 6.4 \pm 0.5$, provides an electron scattering optical depth $\tau_{\rm el} = 0.085 \pm 0.009$. Assuming that all photons are absorbed by the MW environment (mean free path $\lambda_{\rm mfp} \leq 1$ Mpc), we find that at $z \approx 6$ the intensity of UV radiation is $J(\nu_0) \approx 3 \times 10^{-24}(\lambda_{\rm mfp}/\,{\rm Mpc})\,{\rm erg\,s^{-1}\,Hz^{-1}\,cm^{-2}\,sr^{-1}}$. Our findings for $z_{\rm rei}$ are consistent with Busha et al. (2010), (see also Alvarez et al. 2009) who constrained $z_{\rm rei} = 8^{+3}_{-2}$ to match the radial distribution and luminosity function of the MW satellites. Thus, although our model cannot make predictions for how many luminous galaxies survive merging, our inferred history of reionization is consistent with these additional constraints.

Finally, we found that Pop III stars are hosted by low-mass dwarf galaxies, and that they no longer form in the MW environment when $z \lesssim 8$. If the Pop III IMF is biased towards massive stars, then the UV emissivity will naturally increase at $z > 8$, as required by recent models for cosmic reionization. The massive nature of primordial stars has been overlooked recently because of the lack of a clear signature in the chemical abundances of *very* metal-poor stars (e.g. Cayrel et al. 2004; Caffau et al. 2011). These new observational results, however, remain consistent with the predictions of our model for Galactic halo stars, which are independent of the Pop III IMF (SSF07). Thus, we cannot exclude that Pop III stars were massive, as also pointed out by recent simulations ($m_{\rm PopIII} \approx 40\,{\rm M}_{\odot}$ Hosokawa et al. 2011). In conclusion, low-mass dwarf galaxies hosting massive Pop III stars could represent the hidden source of ionizing radiation that is missing at high-z. Hence their impact on MW environment could be even more significant than what is found here by using conservative assumptions.

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